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Two-Phase Thermal Switch for Spacecraft Passive Thermal Management

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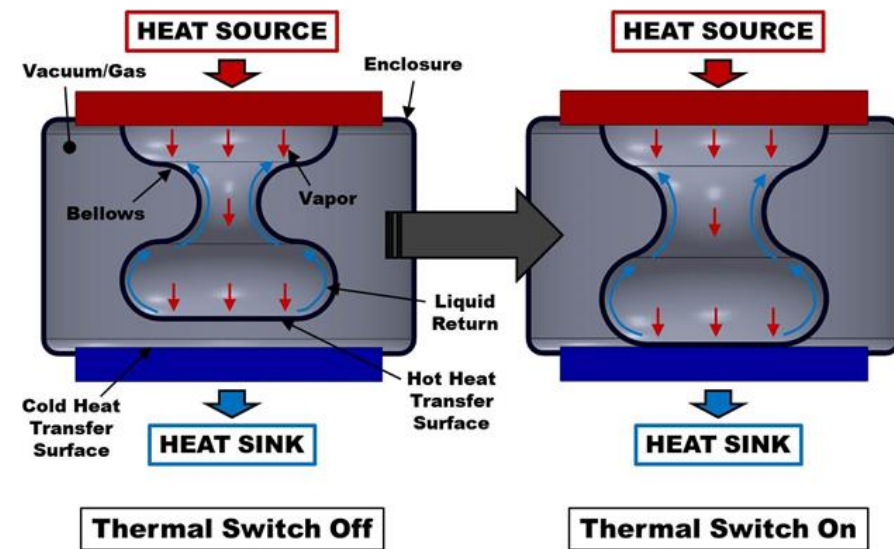
- Thermal management systems with high turndown capabilities are required for future human spacecraft
- Thermal switches are capable of dissipating a wide range of heat loads in widely varying thermal environments with low SWAP
- Lower mass and higher On/Off conductance ratios are desired
- Available Thermal Switch Technologies:
 - Mechanical Thermal Switches
 - Paraffin actuated heat switch, CTE-CTSW, SMA-CTSW
 - Gas-gap Thermal Switch
 - Disadvantages: Complex, expensive, slow response, difficult to manufacture
 - Diode Heat Pipe
 - Disadvantages: High “Off” conductance, 0g concerns, slow response
- Less complex, lower cost alternatives are desired



Two-phase thermal switch concept



- Two-phase thermal switch consists of a metallic bellows encapsulated in a hermetic enclosure
- Uses condensing vapor to both transfer heat and provide pressure for expansion and contact
- Lower complexity, mass, and cost with improved performance
- Works like a vapor chamber or heat pipe with flexible walls
- Vapor pressure is driving force for bellows expansion and contact
- Thermal switch “set point” is the lowest temperature for which the vapor pressure brings the heat transfer surface in contact with the heat sink

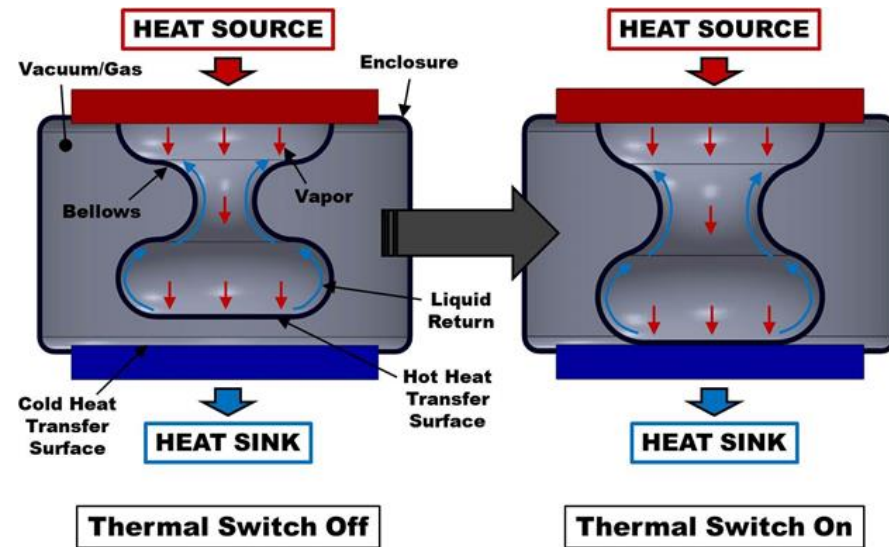




Two-phase thermal switch operation



- One end of bellows is fixed to enclosure, which is in contact with heat source
- Other end of bellows is free
- Capillary wick structure connecting two ends inside bellows
- Heat applied causes working fluid in bellows to vaporize
- Vapor generated causes bellows to expand until contact with heat sink
- When in contact with sink, vapor condenses and is returned to heat source through capillary action in wick
- As some heat is transferred, vapor temperature/pressure in bellows drops – bellows disconnects from sink
- Continued heat application raises temperature and causes bellows to expand again
- Some heat is transferred, bellows disconnects...





Two-phase thermal switch operation



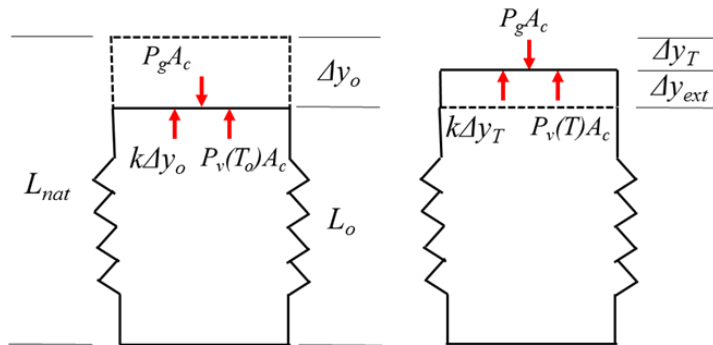
- In normal two-phase thermal switch operation, bellows oscillates in and out of contact with heat sink
- In this way, the vapor temperature inside bellows, and thus the heat source temperature, are approximately held at a “set-point”
- This set-point is determined by vapor pressure required to expand bellows enough to come in contact with sink
- Set point temperature can be manipulated by changing pressure of the gas in the enclosure acting against the bellows
- For high enough powers, the bellows will not disconnect from the sink, and essentially acts as a heat pipe



First order performance model



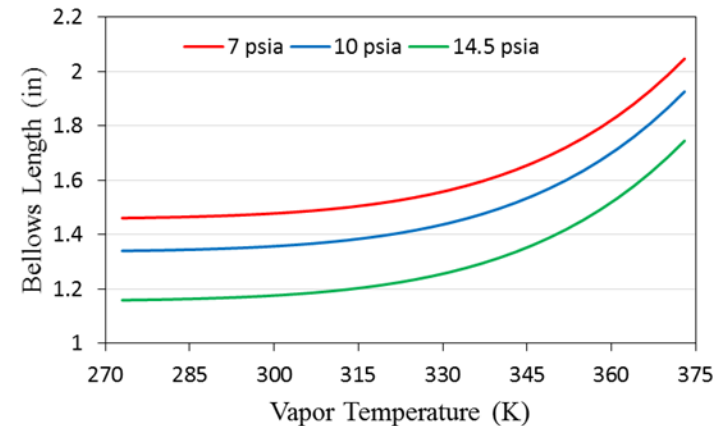
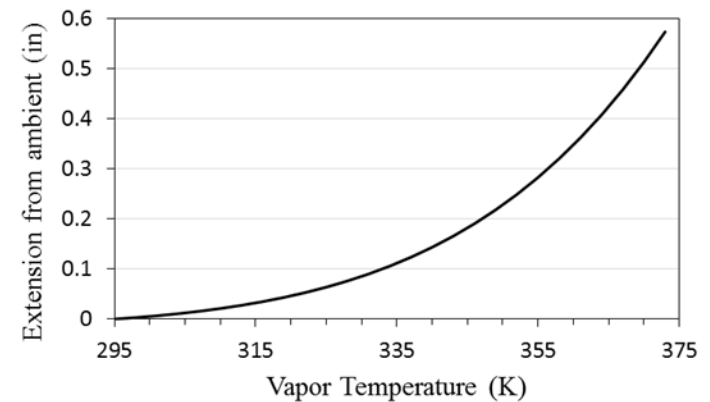
- Static thermo-structural model for predicting thermal switch set point based on force balance



$$\Delta y_o = \frac{A_c}{k} (P_g - P_v(T_o))$$

$$\Delta y_{ext} = \Delta y_o - \Delta y_T = \Delta y_o - \frac{A_c}{k} (P_g - P_v(T))$$

- Static model does not capture full dynamic operation of thermal switch
- Provides basis for full dynamic mode to be developed in the future

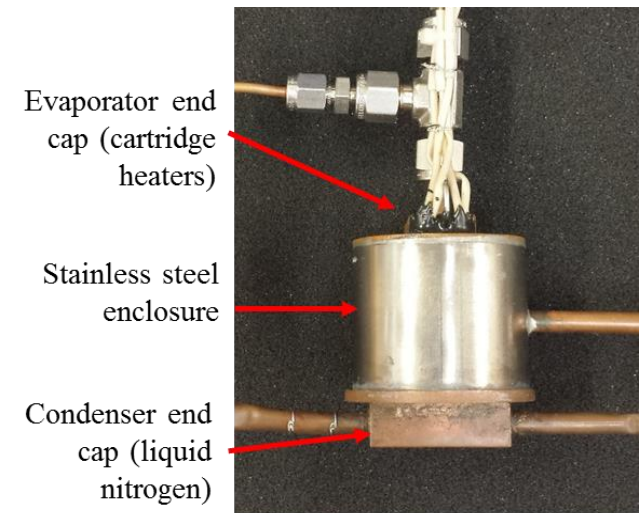
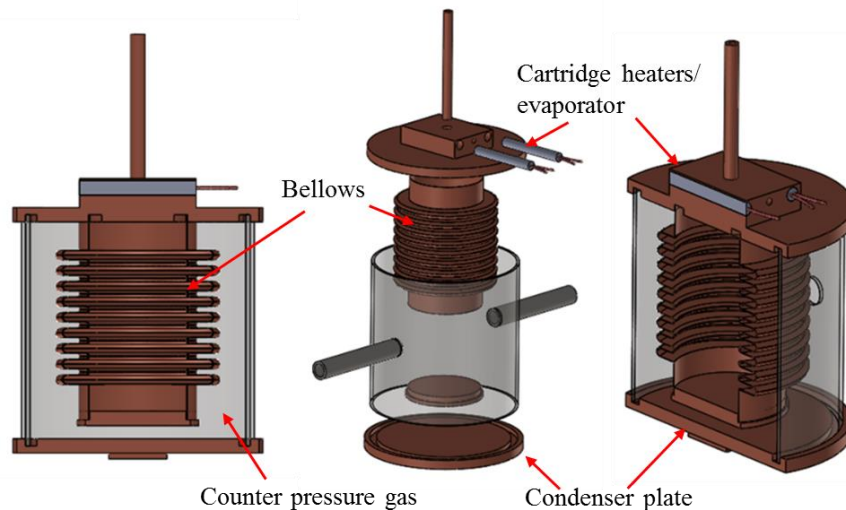




First prototype design



- First prototype designed as a thermosyphon (no wick) for proof-of-concept demonstration
- Beryllium copper bellows (k = 19 lb/in)
- Stainless steel enclosure
- Copper end caps housing heat source and heat sink

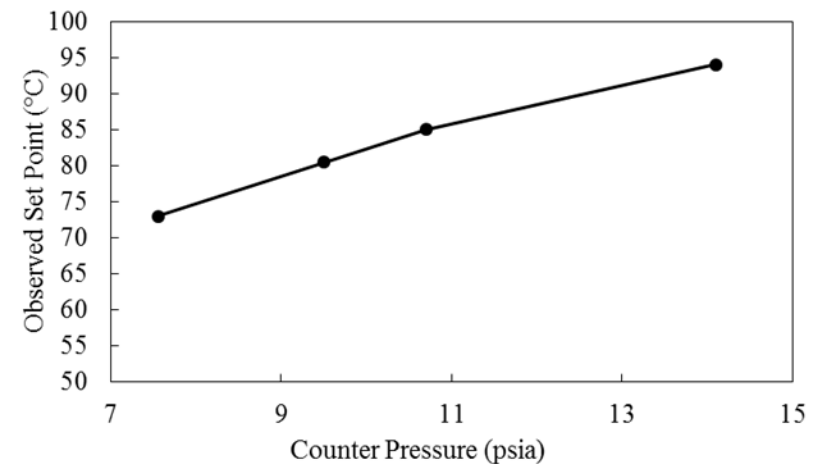
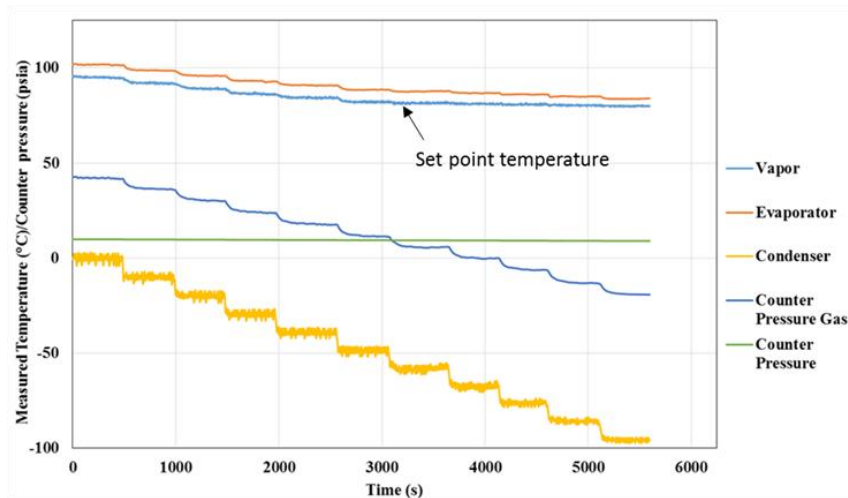




First prototype experimental results



- Testing of first prototype demonstrated ability to maintain heat source set point temperature as heat sink temperature decreases
- Determined heat source set point for several enclosure gas counter pressures, demonstrating ability to manipulate set point by varying the enclosure gas pressure
- Tests also showed that heat leaks through the enclosure are important

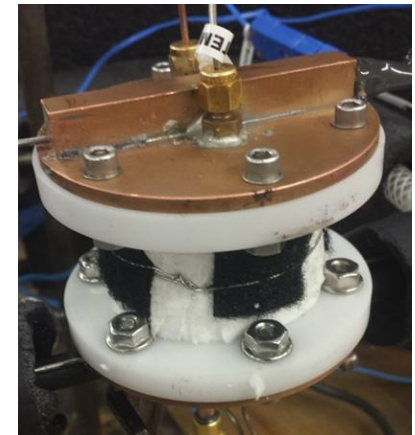
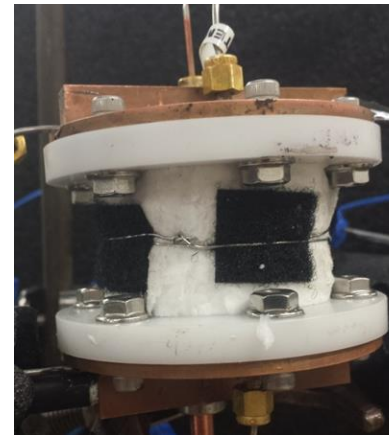
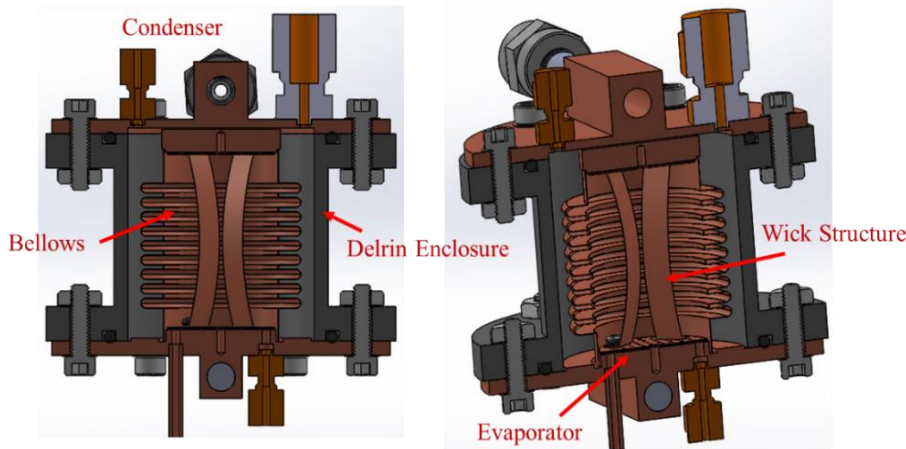




Second prototype design



- Same beryllium copper bellows
- Delrin enclosure to minimize heat leaks
- Copper end caps with incorporated heat source and heat sink
- Copper wick structure in bellows for liquid return

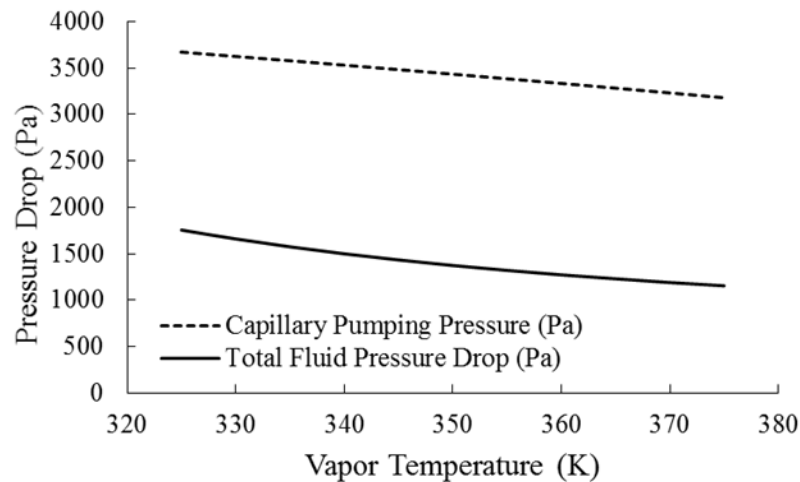




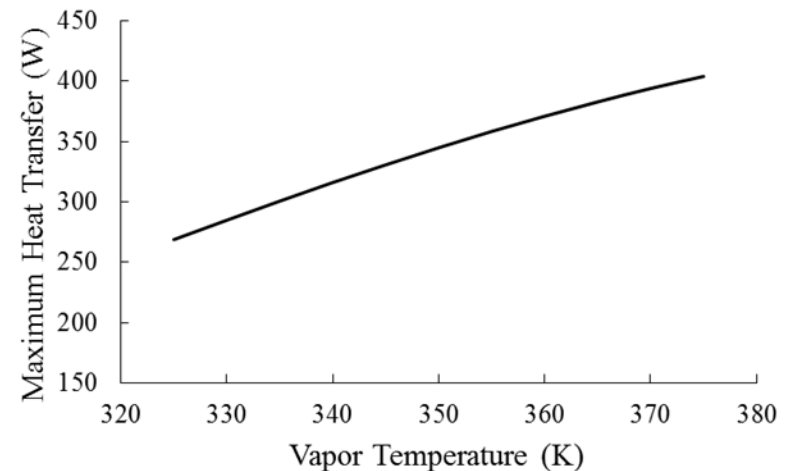
Second prototype design



- Since the two-phase thermal switch is essentially an expandable heat pipe, heat pipe limit calculations were performed
- Capillary limit and predicted maximum power calculated
- Additional performance limits calculated at operating power of 100 W
- Predicts two-phase thermal switch to be operating well below all limits



Capillary limit



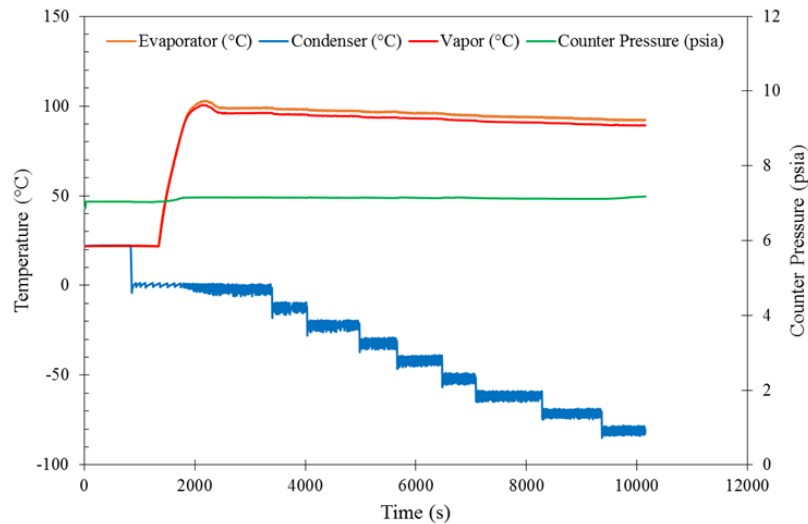
Maximum power



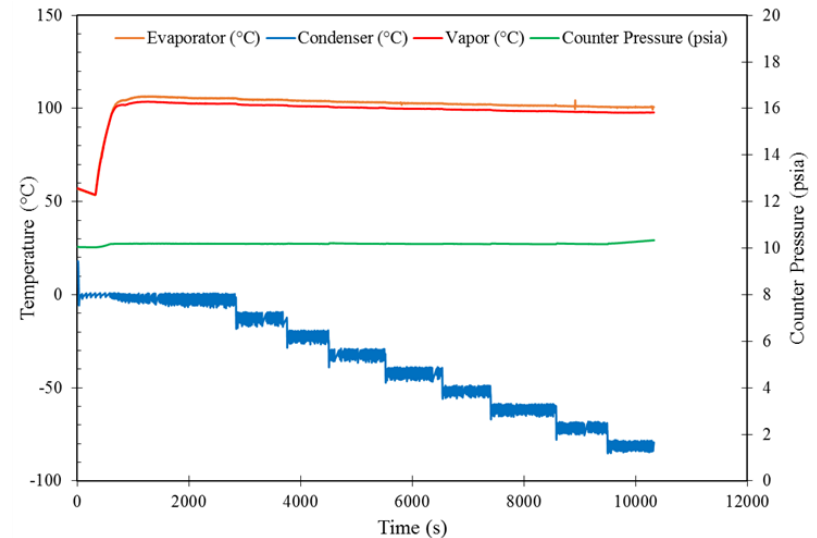
Second prototype experimental results



- Initial tests done heat pipe (against gravity) orientation to demonstrate wicking and orientation independence
- Tests done at multiple counter pressures to determine set point temperature
- Some decay in set point temperature ($\sim 3^{\circ}\text{C}$) as sink temperature drops due to heat leaks through enclosure



7 psia counter pressure



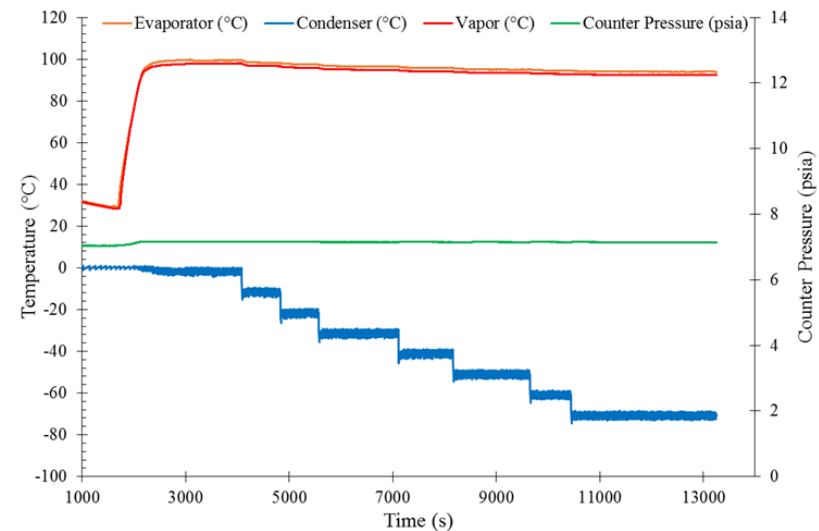
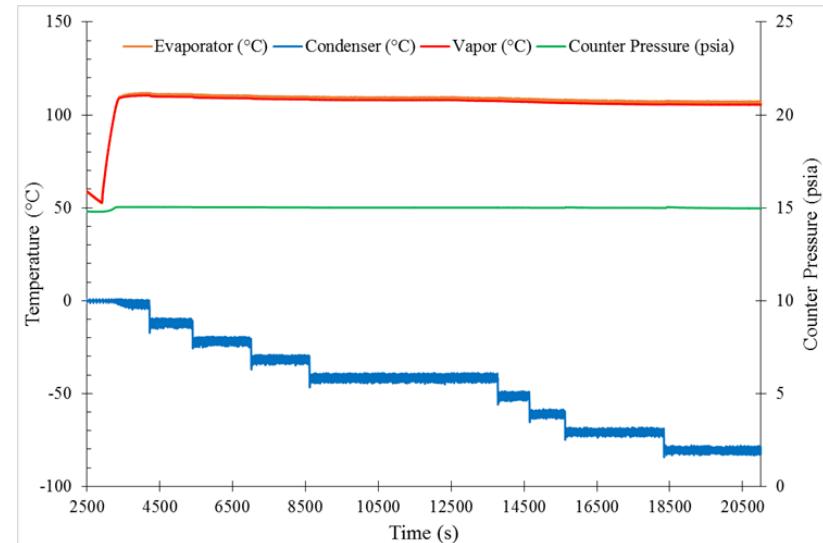
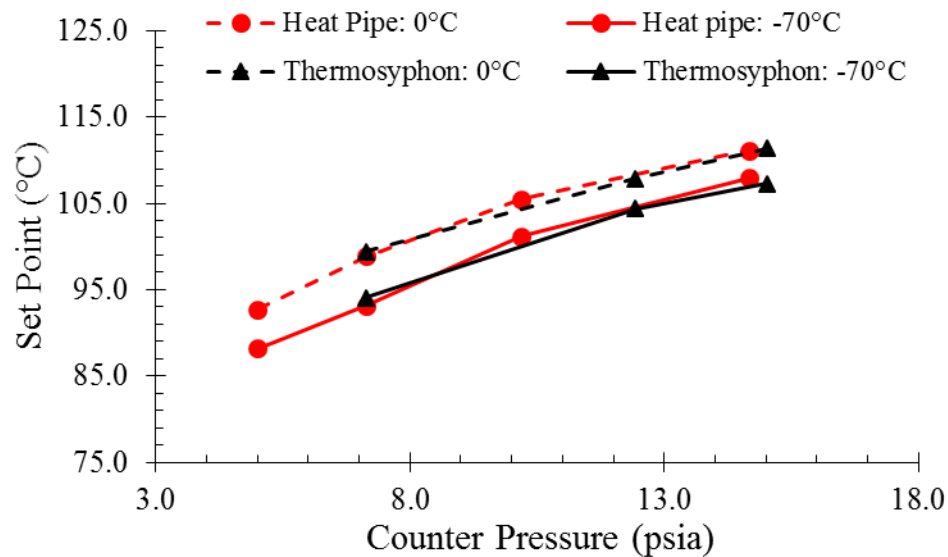
10 psia counter pressure



Second prototype experimental results



- Additional tests performed in thermosyphon orientation (gravity assisted liquid return)
- Set points similar in both orientations –orientation independent operation





Second prototype experimental results



- Thermal conductance testing of second prototype
 - Maximum power applied to determine maximum “On” conductance
 - Power reduced until bellows breaks contact to determine heat leaks – “Off” conductance
 - Heat leaks to ambient characterized
 - On/Off conductance ratios then calculated
 - Evident that “On” conductance and conductance ratio varies with sink temperature due to variable conductance aspect

<u>Case</u>	<u>Maximum Conductance (W/K)</u>	<u>Minimum Conductance (W/K)</u>	<u>Conductance Ratio</u>
14.7 psia, 0° Sink	0.70	0.04	16.1
14.7 psia, -40° Sink	0.56	0.04	14.8
5 psia, 0° Sink	0.69	0.04	17.2
5 psia, -40° Sink	0.64	0.03	20.1
5 psia, 15°C sink	0.74	0.04	19.9

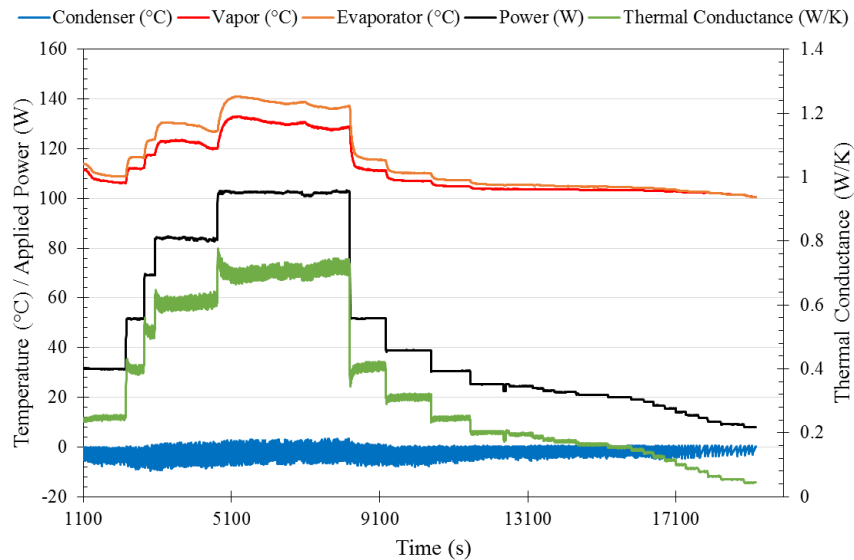
- Thermal conductance of 0.7 W/K and conductance ratio of 20:1 demonstrated



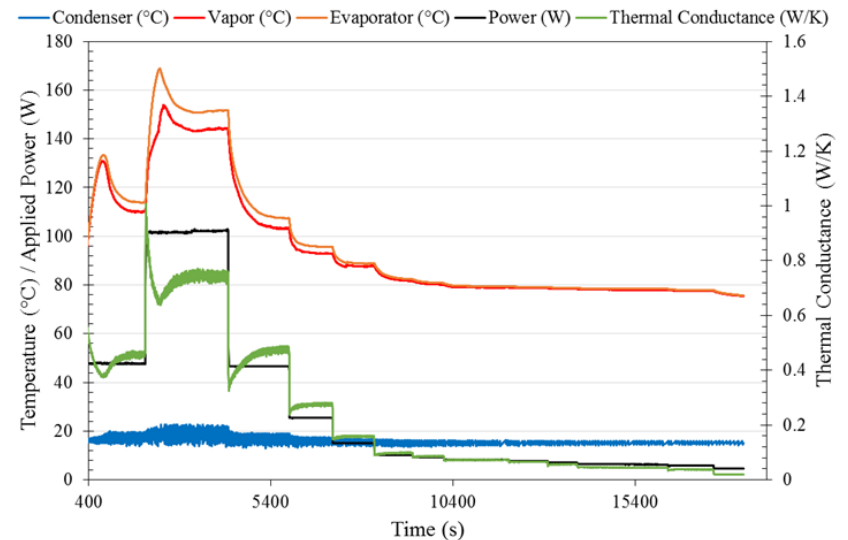
Second prototype experimental results



- Examples of thermal conductance measurement for second thermal switch prototype



14.7 psia counter pressure; 0°C sink



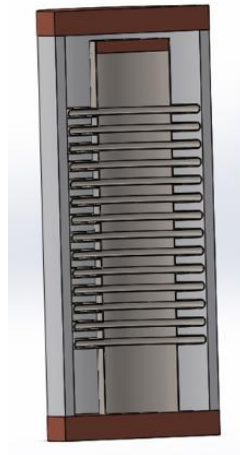
5 psia counter pressure; 15°C sink



Conceptual next generation design



- Prototype two-phase thermal switches were not optimized for mass, but to demonstrate the concept
- A preliminary design was developed for an estimate of the mass of an actual device
 - Ammonia working fluid
 - Stainless steel bellows
 - Ceramic enclosure to reduce heat leaks
 - Copper end caps



<u>Property</u>	<u>Value</u>
Enclosure Material	Ceramic
Bellows Material	Stainless Steel
End Cap Material	Copper
Hot Contact Surface Material	Copper
Ammonia Charge	12mL
Dimensions	2.2in long x 1.0in diameter
Total Mass	0.061 kg

- Total mass of ~61 g much lower than conventional thermal switch technologies



- Dynamic performance model development
 - Transient heat transfer in all components
 - Detailed modeling of fluid and vapor flow in bellows
 - Couple heat transfer model to dynamic spring model of the bellows
 - Changes in enclosure gas pressure due to compression and temperature change
 - Goal of predicting set point temperatures, thermal conductance, and bellows oscillation frequency
- Dynamic performance of two-phase thermal switch is complicated and somewhat unintuitive
- A high-fidelity model will be required for use as a design and optimization tool
- Model also used to predict fatigue life of bellows
 - Two modes of fatigue
 - Large amplitude, low frequency cycles (On/Off)
 - Small amplitude, high frequency cycles (Oscillation during operation)



- Performance improvements
 - Decrease “Off” conductance
 - Enclosure design and materials – reduce heat leaks
 - Increase “On” conductance
 - Reduce contact conductance with TIM and mated surfaces
 - Optimize wick structure
 - Use dynamic model to optimize overall design
- Perform thermal switch life tests
 - Evaluate change in performance due to material wear or bellows fatigue



Conclusions



- Developed a design for a two-phase thermal switch
 - Operates in On/Off mode when heat load is removed
 - Variable conductance device to maintain set point temperature as sink temperature changes
- Initial static model to describe operation
- Prototype demonstration
 - Maintenance of set point temperature
 - Change in set point temperature through change of enclosure gas pressure
- Clear path for improving On/Off conductance ratio
- Mass benefit over existing thermal switch technologies

	<u>Arsys Paraffin</u> <u>TS [1]</u>	<u>JAXA Paraffin</u> <u>TS [2]</u>	<u>ACT TPTS</u>	<u>ACT TPTS Goal</u>
Mass (g)	110	320	~61	< 75
"On" Conductance (W/K)	1.2	1.6	0.7	1.5
"Off" Conductance (W/K)	0.018	0.012	0.04	0.01
On/Off Conductance Ratio	67	127	20	150

■ Conceptual design
■ Measured



Acknowledgments

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- [1] Sunada, E., Pauken, M., Novak, K., Phillips, C., Birur, G., and Lankford, K., “Design and Flight Qualification of a Paraffin-Actuated Heat Switch for Mars Surface Applications.” SAE Technical Paper No. 2002-01-2275, 2002.
- [2] Makiko Ando, Keisuke Shinozaki, Atsushi Okamoto, Hiroyuki Sugita, and Takehiro Nohara. Development of Mechanical Heat Switch for Future Space Missions. 44th International Conference on Environmental Systems. 13-17 July 2014, Tucson, Arizona, USA.